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MECHANISMS OF FIRE SPREAD RESEARCH PROGRESS REPORT NO. 2

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Field Study
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by

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(Field Study)

INTRODUCTION

In 1961 the National Science Foundation awarded grants to Washington State University and the Northern Forest Fire Laboratory of the Intermountain Forest and Range Experiment Station to further a joint study of the mechanisms of fire spread in wildland fuels. The combined efforts of the two research groups encompass theoretical modeling, laboratory studies, and field investigations of the spread of flame fronts. Of these, the modeling and laboratory studies received the most attention (Anderson 1964), but some field burning was considered essential. The basic objectives of field experiments were to test measurement techniques and the adaptability of laboratory instrumentation to field operations, and to determine correlations between laboratory and field test fires.

Several major problems are encountered in attempting to study wildfire fronts and the mechanisms of their spread. The difficulty of study increases with the size and intensity of the fire. Most of these difficulties arise because of:

1. The extreme variability of fuel and of environmental factors along the front.

2. The complexities of measuring and recording fire characteristics in a moving front.

3. The need for remoteness for the safety of personnel, expensive recorders, and other instrumentation.

4. The lack of time needed to set up and describe an area prior to the passage of the front.

5. The present methods of sampling fuel are destructive and do not permit measurement of the same fuel which burns. Destructively sampling fuel near the fire introduces a high probability of collecting fuel that is significantly different from the fuel that burns.

Initial burns used prepared wooden cribs on level ground. This held factors of kind and arrangement of fuel constant. From the experience gained by burning cribs, networks of thermocouples and recorders were developed for recording temperatures. New photographic techniques were designed for use in measuring flame depth, rate of spread, and residence time.

The next step was to burn test fires in prepared slash fuel beds designed to produce low-intensity fires in fuel uniform in material but varied in size. The study was conducted at the Priest River Experimental Forest in northern Idaho during the 1962 fire season. Results from these fires are the basis for this report. Previous studies of fire spread in logging slash were used in designing these fuel beds (Fahnestock 1960). Tree crown logging slash was collected from active logging areas and loaded into carefully controlled fuel beds. After 3 months of curing, the beds were instrumented and burned. To date no attempts have been made to study the flame fronts of large fires in detail. Exploratory photographic measurements have been attempted on large prescribed fires.

METHODS

PREPARATION OF FUEL BEDS

George Fahnestock's work (1960) on logging slash was a guide for establishing the experimental plots. The purposes of his study and the present one were different. Fahnestock was interested chiefly in comparing the influences of species, loading, and aging on burning slash. He was evaluating factors that influence the burning of natural beds of logging slash. The study reported here was designed to relate flame front characteristics to a specific fuel bed. To facilitate the comparison of data from the two studies, fuel beds were loaded at the same weights per acre (7.5, 20.0, and 32.5 tons per acre) as Fahnestock had used. We used slash from lodgepole pine and Douglas-fir, two of the nine species that Fahnestock studied. Rather than using 20- by 20-foot plots with center firing as Fahnestock had, the 1962 plots were 6 by 60 feet and fired at one end to represent a moving segment of a fire front.

Slash was collected, and 24 plots were prepared at the Priest River Experimental Forest in May 1962. Lodgepole pine and Douglas-fir slash from full tree crowns was collected on nearby State of Idaho lands in active logging area. The bole and large tree limbs were not included. Only the tree tip (4 feet to 6 feet) was included with the branches. This slash was hauled to an experimental burning area on a flat at the southwest end of the experimental forest.

Whole-branch samples were selected from the fuel for moisture content determination by xylene distillation. The moisture determi-

Figure 1.— Collecting Douglas-fir slash near the Priest River Experimental Forest.

nations were necessary to calculate the wet weight loading of fuel beds which would yield 7.5, 20.0, and 32.5 tons per acre dry weight.

Boundaries for experimental burning plots were laid out with stakes and strings. Thirty-six 6- by 60-foot plots were staked in 6- by 6- foot increments (10 increments for 60 feet). Some plots were not used because of irregularities or roughness of the ground. Twenty-four plots were assigned fuel loadings by random selection. The plots were replicated four times for the two species and three loadings.

Each deposition of slash filled two 6- by 6-foot squares at a time with a predetermined fraction of the total load placed on a bed (fig. 3). For example, the 7.5-ton beds were loaded at 2.5 tons per layer. One sling load filled a 6- by 12-foot area at 2.5 tons per acre. One complete layer was installed at 6- by 12-foot increments. Then a second layer was added but offset 6 feet so that the placing of layers overlapped the end joints as in brick-work. The third layer was the same as the first. This method of loading provided uniformity both horizontally and vertically. More and thicker layers were used to build the 20.0- and 32.5-tons-per-acre beds.

The plots were located in an enclosed area so that they would not be disturbed by livestock. Weed killers were used to prevent plant growth in the plots. All plots were fully exposed to the elements until July 27. Experimental burning was started at that time and was completed within a week.

FUEL BED SAMPLING

Analyses of the fuel beds included prefire and postfire sampling. Before firing, 12- or 18-foot sections of the fuel beds were destructively sampled to determine the distribution of size classes. Fuel components in sampling sections were carefully measured into five diameter classes: $<1/8$ inch, 1/8 to

Figure 2. — Priest River Experimental Forest outdoor slash laboratory.

1/4 inch, 1/4 to 1/2 inch, 1/2 to 1 inch, and 1 to 2 inches. These size-class measurements were summarized as percents of the total fuel bed ovendry weight. Ovendry weight computations of large segments of fuel sampling beds also provided a cross-check on the weights of plot loadings.

Percentages of moisture content (dry weight basis) were determined by diameter classes to compute size distributions based on ovendry weight. Additional size-class samples were analyzed for moisture content prior to the first fire and following the third fire of each day. Moisture content in fuel elements up to one-fourth inch in diameter was determined by xylene distillation. The larger fuels were dried in an oven at 103° C.

Residue plots were established following three fires to provide estimates of loss of fuel weight during combustion. All ash residue falling within randomized circular plots was collected and weighed, and moisture contents were measured by xylene distillation. The total ovendry weights of residue on the three fires were computed from these data. The fires chosen for residue sampling were Fire No. 7 (Douglas-fir, 32.5 tons/acre), Fire No. 8 (Douglas-fir, 20.0 tons/acre), and Fire No. 10 (lodgepole pine, 32.5 tons/acre). Heat of combustion of the residue was measured in an oxygen bomb calorimeter.

Figure 3. — Slash was weighed in a sling suspended from a scale and then loaded into the plots.

The heats of combustion of the five diameter classes were recorded. Three separate samples were ignited in the bomb calorimeter to determine an average heat value for each size class. Additional sample pellets were dried in an oven at 103° C. to determine moisture content. Determinations of heat of combustion were corrected to ovendry weight, and all heat contents were expressed as the low heat values.[1]

[1]*The low heat value was calculated by assuming that the fuel was 50 percent carbon, 44 percent oxygen, 6 percent hydrogen, and formed 0.539 pound of water vapor for each pound of dry fuel (Fons et al. 1960). This water vapor reduced the high heat value by 0.539 × 972 B.t.u./lb., or 524 B.t.u./lb., due to the latent heat of vaporization.*

INSTRUMENTATION

Since this was the project's first attempt at quanitative field measurements of flame fronts, the number of individual measurements was limited to allow maximum utilization of manpower and instrumentation. Photographic measurement, visual observation, and electronic instrumentation were used to evaluate each method and to provide correlation checks. Measurements made during the burning included photographic recording of the rate of spread, flame depth, flame height, and flame angle; visual observation of rate of spread, wind angle of attack, and fire behavior; and electronic recording of rate of spread, flame depth, vertical temperatures,

Figure 4. — Separating Douglas-fir slash into size classes.

flame base temperature profile, residence time, convection column velocity, and ground wind velocity.

The four instrumentation stations on each fuel bed were set up over the longitudinal centerline of the bed at the 12-, 24-, 36-, and 48-foot points along its length. Twelve stations were fabricated so that fuel beds were intsrumented three at a time.

The instrumentation stations were designed to be as portable as possible. The main support assembly was fabricated in the shape of an "F" with 3/4-inch and 1-inch iron pipe. The leg of the support assembly stood at the side of the fuel bed and fitted into an iron sleeve molded into a portable concrete base. The arms of the "F" assembly reached out over the fuel bed to the centerline. A horizontal bar attached at a right angle to the end of the lower arm of the "F" was parallel to the centerline of the fuel bed. The whole assembly was raised or lowered to position the horizontal bar 6 inches above the mean fuel surface. The top arm of the "F" was 10 feet above the surface of the bed.

Instrumentation on each support assembly consisted of six chromel-alumel thermocouples mounted on the horizontal bar at 9-inch intervals: six chromel-alumel thermocouples mounted on a steel wire stretched vertically from the lower to the upper arms of the "F" (attached 1, 2, 4, 6, 8, and 10 feet above the

Figure 5. — A lodgepole pine plot being burned. Note the four instrumented stations connected by landlines to the monitoring instruments.

fuel bed); and a Kiel probe at the expected vertical height of the flame.

The thermocouple leads were fed through the support assembly pipes to the thermocouple junction position. The signal leads were extended behind the support assembly to an ice bath where reference junctions were made. Landlines carried the signals from the ice bath to a switching box for selection of the desired station signals. From the switching box, signals were fed to two light beam oscillographic recorders. This arrangement allowed monitoring of all four stations of a fuel bed with two recorders by switching as the flame front progressed (figs. 5 and 6).

All thermocouples were butt-welded 24-gage chromel-alumel cut to equal lengths so the total source resistance sensed by the galvanometers was nearly the same. Measurement of the total source resistance showed the maximum variation in any one channel to be 1.72 ohms. Calculation of the change in sensitivity showed the possible variation in indicated temperature at a full-scale deflection would be 4° F. This would be an error of 0.2 percent at a temperature of 2,000° F. The possible error due to the thermocouple material would be 0.75 percent at 2,000° F. The response time of the light beam galvanometers with the equivalent source resistance was 0.05 second for 63 percent of the input change. The thermocouples were the source of greatest inaccuracies because of their time response and errors due to radiation and conduction losses or gains. Using an average velocity of 12 feet per second and 500° F. as the average temperature encountered, the response time of the thermocouples was calculated to be about 1.75 seconds for 63 percent of a step change in temperature. Because of the lag in time response of the thermocouples, the true maximum or minimum temperature may not be indicated. The indicated temperature was felt to be within ±10 percent of the maximum operating temperature for the thermocouple material used.

A microdifferential pressure transducer was used to measure the dynamic pressure in the convection column above the fire. The pressure from Kiel probes over the fire was routed to the transducer, which measured the differ-

Figure 6. — A closeup of the horizontal bar attached to each instrumented station.

ential pressure (ΔP) between a selected probe and atmospheric pressure. The convection column temperature was taken simultaneously with the dynamic pressure so that the convection column velocity at that point could be computed.

The Kiel probes were at fixed heights of 4, 7, and 10 feet above the fuel beds. Once attached to stations, these probes could not be moved during the fire; consequently, the readings came sporadically as wind allowed the fire to stabilize beneath a probe. A probe on each of the four stands permitted four opportunities to obtain useful data as the fire traveled along the 60-foot fuel bed.

In addition to the instruments at the stations, a directional hot wire anemometer was positioned 5 feet from the edge of the fuel bed, 3 feet above the ground and aligned with the fuel bed to measure the ground wind velocity. A wind speed and direction indicator was positioned similarly to determine wind direction.

A specially modified battery-powered motion picture camera was set up on a tripod at right angles to the length of the fuel bed. An electronic timer and battery-powered motor drove the camera for 6 seconds at 1-minute intervals. High-speed color film (ASA 160) permitted rapid exposure with good resolution.

Three new fuel beds were selected and instrumented each day, alternating between Douglas-fir and lodgepole pine. One bed of each loading (7.5, 20.0, and 32.5 tons per acre) was burned each day. Replicates were chosen at random. Burning always progressed from the heaviest loading to the lightest in sequence, and all plots were burned from south to north.

MEASUREMENTS

Rate of spread. — Rate of spread of the flame front was recorded for later analysis on motion picture film and by temperature traces of evenly spaced thermocouples on oscillograph recorders. The photographic data were taken in 6-second bursts (32 frames per second) at 1-minute intervals. Rate of spread was determined by scaling the distance the fire advanced in 1 minute.

Thermocouples were located at 9-inch intervals at each station. As the fire passed, the temperature rise was recorded by the oscillograph. Rate of spread was then taken from the temperature rise times of the traces as the fire moved from thermocouple to thermocouple. Since stations were spaced 12 feet apart, the rate of spread from station to station was also measured. The rate of spread from the first to last thermocouple at each station provided a third method of measuring rate of spread.

Flame depth. — Flame depth is defined by the distance from the leading edge of the frame front to the rear edge of the solid flaming area. Flame depth was measured directly from the photographic data. The flame depth was also calculated from the thermocouple residence time data using the formula
$D = R_s \times T_r$
where

D = flame depth—ft.
R_s = rate of spread—ft./min.
T_r = residence time—min.

Residence time is defined as the length of time the flame is supported at a fixed location. Residence time may be taken from a thermocouple trace between the time of temperature rise to the time the temperature starts to drop.

Combustion rate. — The measured flame depth, rate of spread, and pounds of fuel per square foot were combined to determine rate of combustion of fuel in pounds burned per square foot per minute. We assumed that all the fuel was consumed by the flame front. The following equation describes the combustion rate per unit area:

$$G = \frac{R \times W}{D}$$

where

G = burning rate—lbs./ft.^{2}/min.

R = rate of spread—ft./min.

W = weight of fuel burned per unit area —lb./ft.^{2}

D = depth of flaming zone—ft.

Other studies (Thomas et al. 1961; Fons et al. 1962) show a correlation between flame length over flame depth and burning rate.

The equation used by Thomas was:

$$\frac{L}{D} = f\left(\frac{Q^2}{gD^5}\right)$$

where

L = flame length—ft.

D = flame depth—ft.

Q = volumetric flow of gaseous fuel—ft.³/min.

g = acceleration due to gravity—ft./min.²

Fons used a similar equation:

$$\frac{L}{D} = f\left(\frac{C^2G^2}{\rho^2 gD}\right) = f\left(\frac{V^2}{gD}\right)$$

where

C = lbs. of gas produced per lb. of fuel

G = burning rate—lbs./min./ft.²

ρ = density of gases—lb./ft.³

g = acceleration due to gravity—ft./min.²

V = combustion gas velocity—ft./min.

In either case, g is present to make the functional relation dimensionless and indicates the process is gravitationally controlled. These relations can be extended to make the function dependent upon G, the unit area burning rate:

$$\frac{L}{D} = f\left(\frac{Q^2}{gD^5}\right) = f\left(\frac{V^2}{gD}\right) = f\left(\frac{G}{\rho(gD)^{1/2}}\right)$$

A later study (Thomas 1963) showed that the relation held for several types of fuel media and included some of Fons' (1960) earlier work. This indicated the probability of any diffusion type flame fitting somewhere along this curve (Thomas 1961, 1963).

Vertical temperature profile. — The vertical thermocouples at each station produced measurements of the temperature gradient from points 6 inches to 10 feet above the fuel surface. The maximum temperature zone was determined for each elevation in each fuel type and loading. The average temperature was then determined at each elevation.

Fuel compactness. — One of the most difficult fuel bed parameters to assess is the compactness[2] of the fuel bed. Tests conducted to determine the influence of compactness on rate of spread (Curry and Fons 1939) showed rate of spread to be proportionate to the square root of λ (volume per surface area).

In order to evaluate compactness, the following items must be determined:

1. Volume of fuel bed. This factor can be obtained easily for prepared fuel beds. For prescribed fires and uncontrolled fires, considerable difficulty arises.

2. Weight of the fuel bed or loading. The statements in 1 above apply to this factor.

3. Fuel size and proportion of total weight. For laboratory fires where only needles are used, no difficulty exists. For tests where slash is used or for other fires mentioned above, destructive sampling is necessary.

4. Density of fuel particles. Values are available for needles and wood and are usable for specific fuel beds of these materials. When the fuel particles can be a combination, the needles become one size class and the twigs and branches are broken into size classes and given an estimated density.

5. Fuel particle surface area-to-volume ratio. Past studies by Curry and Fons (1939) and Fons (1946) provide values for various fuels. Not all fuels are covered, and additional studies are needed. Since the values for the above factors are known, the compactness of each fuel bed can be calculated.

The equation for compactness is:

$$\frac{1}{\lambda} = \frac{\Sigma(\sigma_1 V_1 - - - \sigma_n V_n)}{V_T - \Sigma\left(\frac{\%_1 W_T}{\rho_1} - - - \frac{\%_n W_T}{\rho_n}\right)}$$

where

$\frac{1}{\lambda}$ = compactness—ft.²/ft.³

σ = surface area-to-volume ratio for size—ft.²/ft.³

V = volume for size class—ft.³

$\% W_T$ = percent of fuel bed weight for size class—lbs.

ρ = density for size class—lb./ft.³

[2] *Fuel bed compactness is defined as the surface area of the fuel divided by the void volume of the fuel bed (ft.²/ft.³). The void volume of the fuel bed is the total geometric volume minus the volume occupied by the fuel.*

WEATHER

All experimental plots were burned in very dry, hot weather during the period July 27 through August 2, 1962. Accumulative drying had been so good that the logging slash was thoroughly seasoned and highly flammable. A condensed record of the weather on the burning days is shown in table 1.

Table 1. — Weather observations at test fire site

Date	Hour	Dry bulb	Wet bulb	Humidity	Average wind	Fire number and hour test fire was ignited	
		°F.	°F.	Percent	M.p.h.		
7/27/62	0900	70	60	57			
	1250	87	64	28	4.0	1	1250
	1345	87	64	28	4.5	2	1345
	1440	90	64	24	4.0		
						3	1500
	1620	90	64	24	3.0		
7/28/62	1550	94	64	18	7.0		
	1620	93	64	20	5.0	4	1630
						5	1731
	1800	92	64	21	7.0		
						6	1815
7/30/62	0840	68	57	52	1.5		
	1000	79	61	36	3.0		
	1100	81	61	32	3.0		
						7	1126½
	1200	85	62	27	7.5		
						8	1209
	1255	89	63	23	4.5	9	1254¼
	1725	90	63	21	4.0		
7/31/62	0820	68	58	56	4.0		
	1000	81	61	32	5.0		
	1115	85	63	30	3.5		
	1320	90	63	21	3.0		
						10	1351
	1410	93	63	18	3.5		
						11	1449
	1525	94	63	16	5.0		
						12	1536
	1620	92	62	17	6.5		
8/1/62	1100	83	63	33	4.0		
	1400	90	65	26	5.5		
	1645	91	64	22	2.0		
						13	1700
	1725	92	64	21	4.0		
						14	1735½
	1800	92	64	21	2.0		
						15	1820
	1845	82	64	38	1.0		
8/2/62						16	1031
	1036	71	62	61	2.5		
	1115	70	61	61	0.5		
						17	1133
	1213	78	63	44	6.0		
						18	1258½
	1323	80	64	42	4.0		

EXPERIMENTAL RESULTS

FUEL BED EVALUATIONS

Diameter size class distribution. — The size class distribution indicated that the fine fuel components (fuels one-fourth inch and smaller) comprised 39 percent of the lodgepole pine and 34 percent of the Douglas-fir fuel beds on an ovendry weight basis (table 2). An intraspecies comparison presented a fair degree of uniformity of fuel bed loadings by size class. Interspecies loading differences appeared when the average percent of total fuel bed weight of lodgepole pine was contrasted with that for Douglas-fir. Lodgepole pine fuel beds usually contained a greater percentage of branchwood in the 1/8- to 1/4-inch and 1/4- to 1/2-inch size classes. The other size class where the species' percentage composition differed markedly was from 1 to 2 inches. Twenty-seven percent of the Douglas-fir fuel and 14 percent of the lodgepole pine were this larger branchwood.

Table 2. — Percent of total fuel bed weight (ovendry), by diameter size class and loading, for lodgepole pine and Douglas-fir

Diameter size class (inches)	Lodgepole pine			Douglas-fir			Average percent of total weight by diameter size class	
	Loading (tons per acre)							
	7.5	20.0	32.5	7.5	20.0	32.5	L.P.P.	D.F.
<1/8	22.33	19.87	26.69	15.97	32.16	32.27	22.93	28.14
1/8 - 1/4	12.64	17.61	18.38	5.14	6.46	3.99	16.21	5.51
1/4 - 1/2	26.94	20.50	20.41	9.03	10.98	9.68	22.62	10.17
1/2 - 1	29.50	23.60	20.66	28.25	31.23	25.60	24.59	29.08
1 - 2	8.59	18.42	13.86	41.61	19.16	28.46	13.62	27.10

Fuel bed loading. — The determinations of ovendry weight of large portions of fuel beds permitted the comparison of the actual fuel bed weights with the theoretical fuel bed weights (table 3). During preparation of fuel beds, concurrent moisture content measurements of the slash determined the weight (ovendry basis) of material needed to achieve loadings equaling 7.5, 20.0, and 32.5 tons per acre. Duplicating these loadings required the placement of 120, 320, and 520 pounds, respectively, on the 6- by 60-foot plots. Success in closely approximating the theoretical pounds of fuel (ovendry basis) required per loading depended largely on moisture fluctuations within the fuel. These results reflect the conditions under which the fuels were collected. Lodgepole pine, which deviated very little from the theoretical loadings, was collected from trees during an active logging operation. Therefore, moisture was relatively uniform throughout the slash. Douglas-fir was collected several weeks after logging, and actual loadings deviated considerably from theoretical loadings.

Table 3. — **Deviations of weights of fuel in beds from theoretical ovendry weight loadings**

Loading (tons/acre)	Theoretical bed weight	Lodgepole pine actual bed wt.	Deviation	Douglas-fir actual bed wt.	Deviation
	Lbs.	Lbs.	± (lbs.)	Lbs.	± (lbs.)
7.5	120	122.4	+ 2.4	181.6	+61.6
20.0	320	336.0	+16.0	266.6	−53.4
32.5	520	522.7	+ 2.7	486.5	−33.5

Moisture content. — Moisture content of fuel was measured before the first fire and after the third fire on each day. Fuel moisture content of the second fire was computed by straight-line interpolation. Almost without exception, fuels in the three larger size classes did not vary in moisture content during an afternoon's burning (table 4). The time lag of the two smaller size classes was short enough to produce diminishing moisture trends in most instances.

Table 4. — **Moisture content of lodgepole pine and Douglas-fir slash by size class**

Fire number	Species	Loading	Moisture content (by size class)				
			<1/8"	1/8-1/4"	1/4-1/2"	1/2-1"	1-2"
		Tons/acre	Percent				
1	Fir	32.5	7.9	8.9	10.8	9.9	12.1
2	Fir	20.0	7.3	8.5	10.8	9.9	12.1
3	Fir	7.5	6.5	8.0	10.8	9.9	12.1
4	Pine	32.5	8.1	8.1	11.8	14.2	14.0
5	Pine	20.0	7.5	7.9	11.8	14.2	14.0
6	Pine	7.5	7.1	7.7	11.8	14.2	14.0
7	Fir	32.5	6.9	7.1	8.0	9.3	9.4
8	Fir	20.0	6.6	6.8	8.0	9.3	9.4
9	Fir	7.5	6.2	6.4	8.0	9.3	9.4
10	Pine	32.5	5.8	6.8	8.5	9.5	10.4
11	Pine	20.0	5.8	6.8	7.8	9.1	10.4
12	Pine	7.5	5.8	6.8	7.4	9.0	10.4
13	Fir	32.5	5.4	6.1	9.8	10.3	11.6
14	Fir	20.0	5.4	6.1	9.8	10.3	11.6
15	Fir	7.5	5.4	6.0	9.8	10.3	11.6
16	Pine	32.5	8.4	7.8	10.3	9.5	10.3
17	Pine	20.0	7.8	7.6	10.3	9.5	10.3
18	Pine	7.5	7.4	7.4	10.3	9.5	10.3

Table 5. — Heat of combustion of lodgepole pine and Douglas-fir by size class

Diameter size class (inches)	Heat of combustion[1] Lodgepole pine	Heat of combustion[1] Douglas-fir
	B.t.u./lb.	B.t.u./lb.
<1/8	[2]8713 ± 12.39	8139 ± 22.08
1/8 - 1/4	8704 ± 6.69	8524 ± 16.54
1/4 - 1/2	8519 ± 31.61	8305 ± 17.43
1/2 - 1	8397 ± 49.76	8268 ± 18.70
1 - 2	8455 ± 26.74	8451 ± 18.15

[1]Expressed as low heat value on ovendry basis.
[2]The ± values are standard errors of the mean.

Table 6. — Heat of combustion of residue and fuel bed weight loss

Fire	Heat of combustion[1]	Weight of residue	Fuel bed weight loss	Weight loss
	B.t.u./lb.	Lbs.	Lbs.	Pct.
No. 7 Douglas-fir 32.5 T/A	[2]5365 ± 20	51.75	434.75	89
No. 8 Douglas-fir 20.0 T/A	8016 ± 278	45.12	221.48	83
No. 10 Lodgepole pine 32.5 T/A	9041 ± 184	39.37	483.33	92

[1]Expressed as low heat value on ovendry basis.
[2]The ± values are standard errors of the mean.

Heat of combustion. — Heat values by size class were determined for both species (table 5).

The heat of combustion of the residue was determined for three fires and weight loss of fuel beds was computed (table 6).

Fire intensity. — In order to compare fires burned at different times, under different loading conditions, or using different fuel types, some measurement of fire intensity was necessary. Comparing only rates of spread was not sufficient since laboratory studies have shown that two fires in different fuels may have the same rate of spread but different rates of fuel consumption. If fuel consumption rate could be measured in the field, then a means of comparison would be available. Since equipment to do this was not available, other measurements were used.

Byram defined fire intensity as the rate of energy release, or rate of heat release, per unit time per unit length of fire front (Davis et al. 1959). In equation form, fire intensity can be written as:

$$I = HWR$$

where

I = fire intensity in B.t.u. per unit time per unit length of fire front

H = heat yield in B.t.u. per pound of fuel

W = weight of available fuel per unit area

R = rate of spread in unit length per unit time.

Use of this equation can give some numerical concept for comparing individual fires but may be deceptive if no other fire parameter than rate of spread is used. Fons et al. (1962) extended this equation and showed a relation between flame length and fire intensity. This relation can be described mathematically by $L = 0.74(HWR)^{.667}$ where L is flame length. The results of the test field fires were analyzed and plots made for the fuel types (table 7 and fig. 7). For lodgepole pine we found $L = 0.43(HWR)^{0.651}$ and for Douglas-fir $L = 0.26(HWR)^{0.670}$. The heat yield was assumed to equal the heat of combustion for this analysis.

The results were compared with those from Project Fire Model (fig. 7) and showed essentially the same slope for all fires. However, each fuel had a separate curve. If fires in each fuel produced flame lengths of 60 inches, intensities varied from 715 B.t.u./min./in. for Fire Model cribs to 3390 B.t.u./min./in. for Douglas-fir slash. This demonstrated that a single curve did not satisfy fire conditions in all fuels. Thus, more investigation is required before a complete description can be made.

As a relative measure, fire intensity can be useful. The three fires analyzed for residual heat of combustion were used to determine where the test field fires would fall on the intensity scale (table 8).

Before fire intensity can be described numerically, the heat yield of the fuel must be defined. This heat yield is equal to the heat of combustion minus the heat losses resulting from radiation, vaporization of moisture, and incomplete combustion (Davis et al. 1959).

Table 7. — Fire intensity test data

Fuel type and loading (tons/acre)		Loading	Heat value	Rate of spread	Rate of spread	Fire intensity	Fire intensity	Flame length
		Lbs./ft.^{2}	B.t.u./lb.	Ft./min.	Ft./sec.	B.t.u./sec./ft.	B.t.u./min./in.	Inches
Douglas-fir:								
32.5	1	1.35	8292	5.15	0.086	963	4815	71.8
	2	1.35	8292	7.20	0.120	1343	6715	76.8
	3	1.35	8292	5.40	0.090	1007	5035	85.1
20.0	1	0.74	8281	5.05	0.084	515	2575	48.8
	2	0.74	8281	4.82	0.080	490	2450	49.7
	3	0.74	8281	3.39	0.056	343	1715	46.5
7.5	1	0.50	8340	2.59	0.043	179	895	31.7
					0.088	367	1835	31.1
	3	0.50	8340	—	—	—	—	30.0
Lodgepole pine:								
32.5	1	1.45	8571	3.53	0.059	607	3035	101.5
	2	1.45	8571	3.40	0.057	708	3540	86.0
	3	1.45	8571	4.80	0.080	994	4970	114.2
20.0	1	0.93	8550	5.90	0.098	779	3895	79.0
	2	0.93	8550	2.70	0.045	358	1790	70.0
	3	0.93	8550	1.79	0.030	238	1190	47.2
7.5	1	0.34	8544	4.70	0.078	226	1130	41.8
	2	0.34	8544	5.22	0.087	253	1265	45.2
	3	0.34	8544	—	—	—	—	45.8

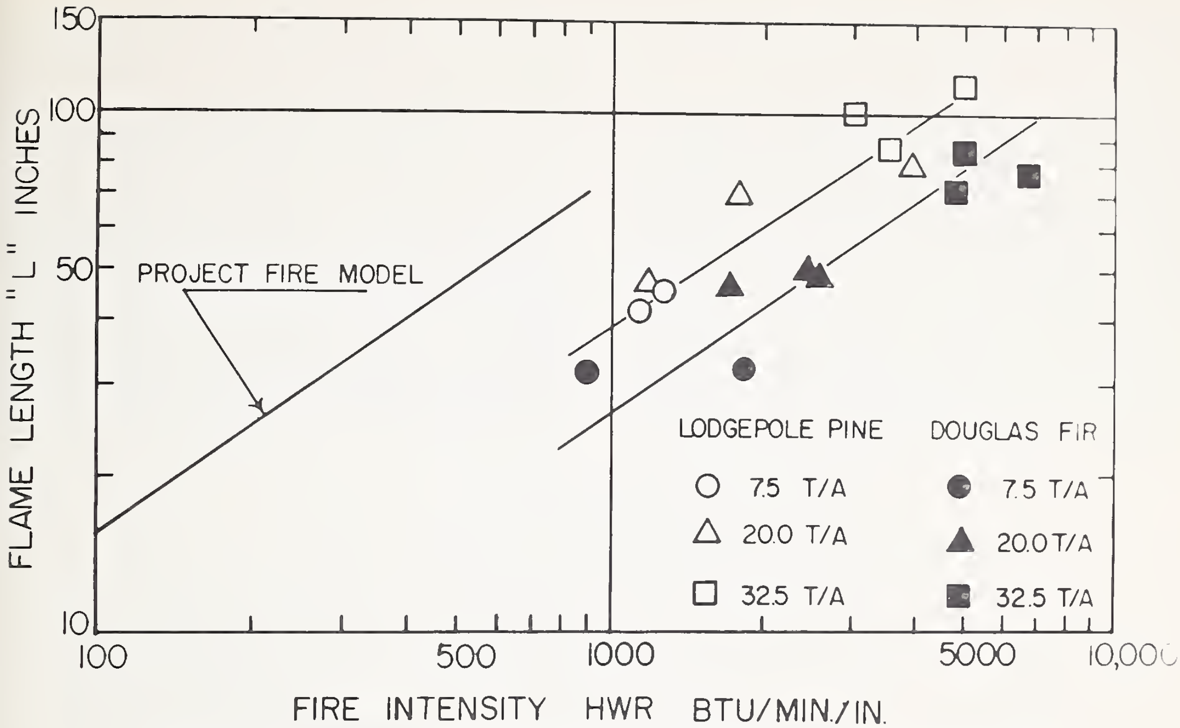

Figure 7. — Flame length as a function of fire intensity for three different fuels in two different fuel beds.

Table 8. — **Fire intensity based on equation I = HWR**

Fire number	Species	Loading	Heat yield (H) [1]	Fuel weight (W)	Rate of spread (R)	Intensity
		Tons/acre	B.t.u./lb.	Lbs./sq. ft.	Ft./sec.	B.t.u./ sec./ft.
7	Douglas-fir	32.5	6715	1.35	0.129	1169
8	Douglas-fir	20.0	6680	0.74	0.064	316
10	Lodgepole pine	32.5	7145	1.45	0.059	611

[1]Heot yield is defined as the heot of combustion minus the heat losses due to rodiation, voporizotion of water, and inefficient combustion. For eoch fuel, rodiotional heot loss wos established as 800 B.t.u./lb. and latent heat of vaporization loss os 524 B.t.u./lb. Heat losses due to incomplete combustion voried by fire as follows: (1) Fire 7, 570 B.t.u./lb., (2) Fire 8, 1357 B.t.u./lb., and (3) Fire 10, 681 B.t.u./lb. These values represent fuel energy thot was not released, rother than octual heot losses.

Byram states that radiation accounts for 10 to 20 percent of the heat of combustion. He feels that a 10-percent loss might be a more realistic figure since some of the radiated heat is returned to the active fire system in preheating unburned fuel. The heat balance developed by Fons et al. (1960) contributed 18.1 percent of the total heat value of the fuel to radiation. In the Priest River analysis the radiational heat loss was arbitrarily set at 800 B.t.u. per pound — slightly less than a 10-percent deduction.

The heat loss due to the vaporization of the water of reaction was accounted for. All measurements of heat of combustion were expressed in terms of the low heat value, which reduces the high heat value by the

latent heat of vaporization (524 B.t.u./pound).

The heat loss due to incomplete combustion is not known for forest fires. However, combustion inefficiency must be determined to compute heat yield of a fuel. Sampling residual fuel weight and residual heat of combustion following three fires provided this necessary heat loss data.

Byram reports that a majority of wildfires probably has intensities in the range from 100 to 1,000 B.t.u. per second per foot of fire front (1959). Intensity values of these experimental field fires fall within this proposed wildfire range.

FIRE CHARACTERISTICS

Rate of spread. — Only a few fires showed a uniform rate of spread from beginning to end. Most variations in rate of spread for individual fuel beds could be attributed to changes in wind velocity. Since the photographic measurements of rate of spread at 1-minute intervals did not give uniform rates for the fuel beds, the average for the beds

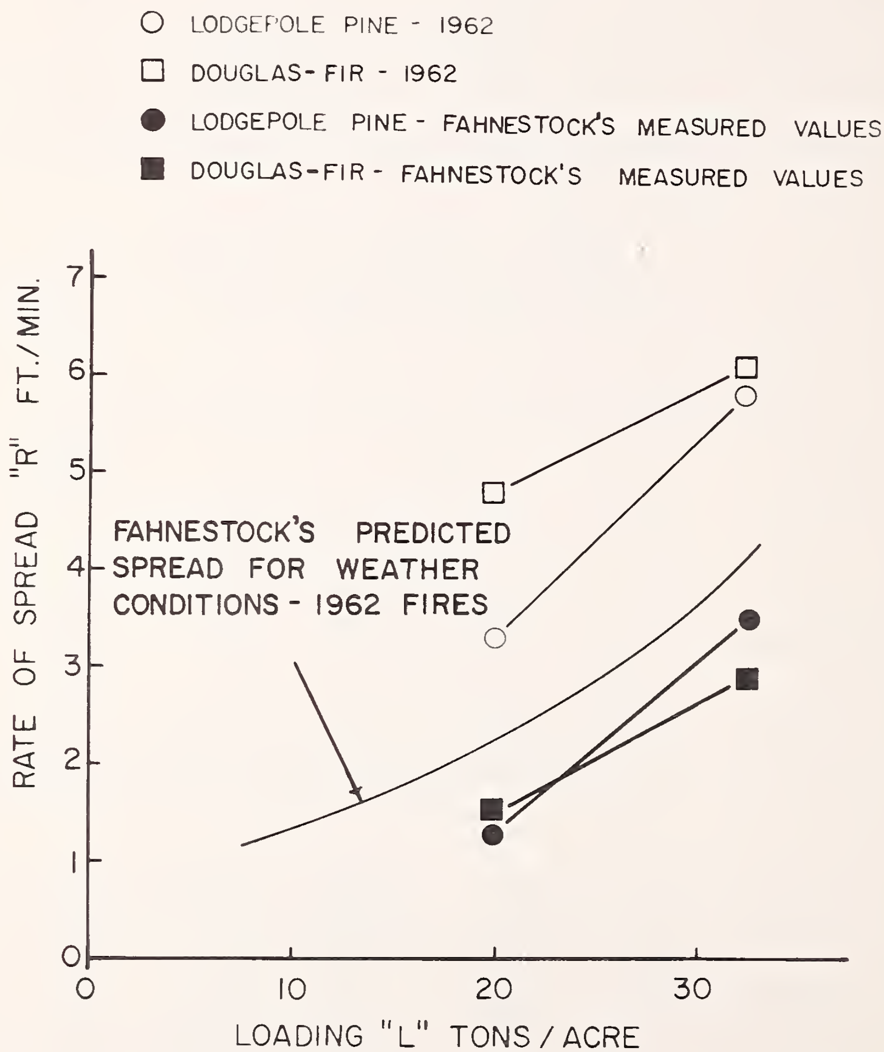

Figure 8. — Influence of loading on rate of spread in fuel beds either end-fired or center-fired.

was used. Average rates of spread for the full length of the plots for each species by loading are shown in figure 8. Most of the 7.5-ton-per-acre beds did not burn for the full length and therefore are not plotted in figure 8. Fahnestock's (1960) results for the same species and loading are presented for comparison. The curves are very similar but his rates of spread were much lower. This can be accounted for by the less severe weather Fahnestock encountered during his experiments. Too, Fahnestock center-fired his plots; this caused an inflow of air to the convection column that further retarded the forward movement of the flame front.

Rates of spread shown by the thermocouples were even more erratic. The thermocouples were apparently too high (6 inches) above the fuels; this allowed them to be alternately in or out of the flame as it moved about in the air currents. Better results probably would have been achieved if the thermocouples had been placed at the fuel surface. By utilizing the longer spans between the first and last couples at a station, or the

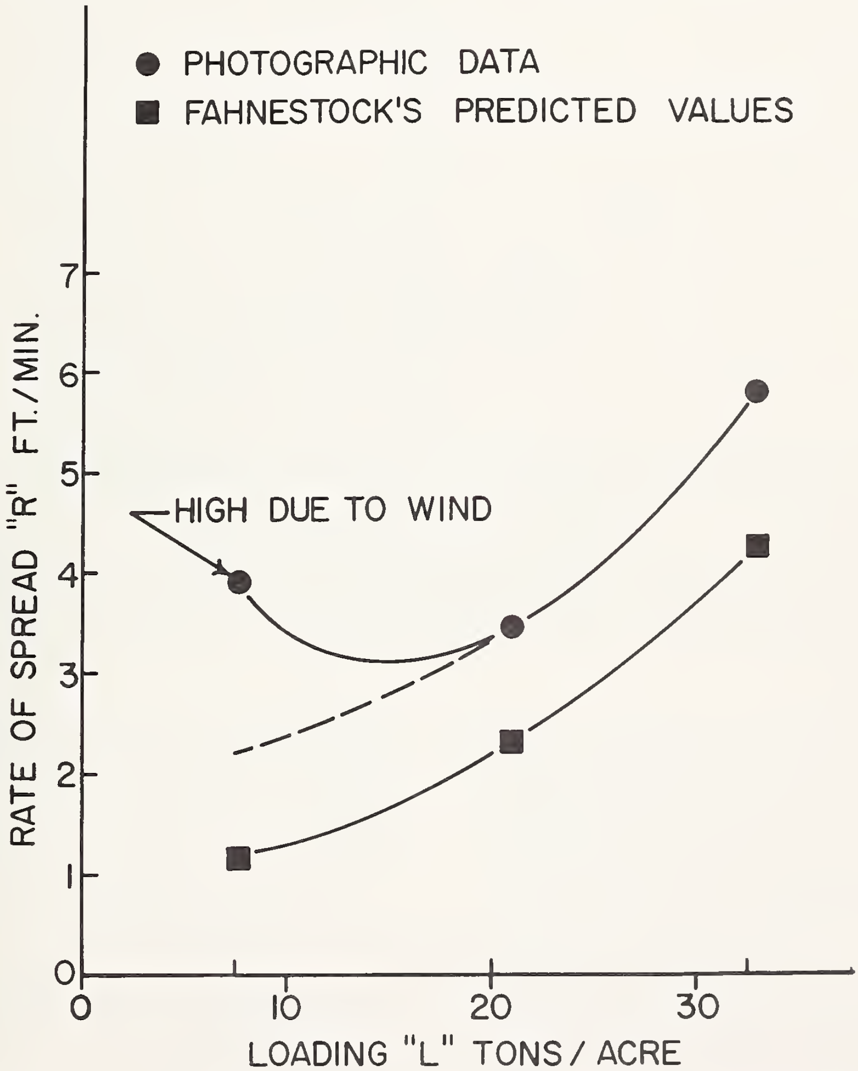

Figure 9. — Influence of loading on rate of spread in lodgepole pine comparing photographic average values with predictions from Fahnestock's equations.

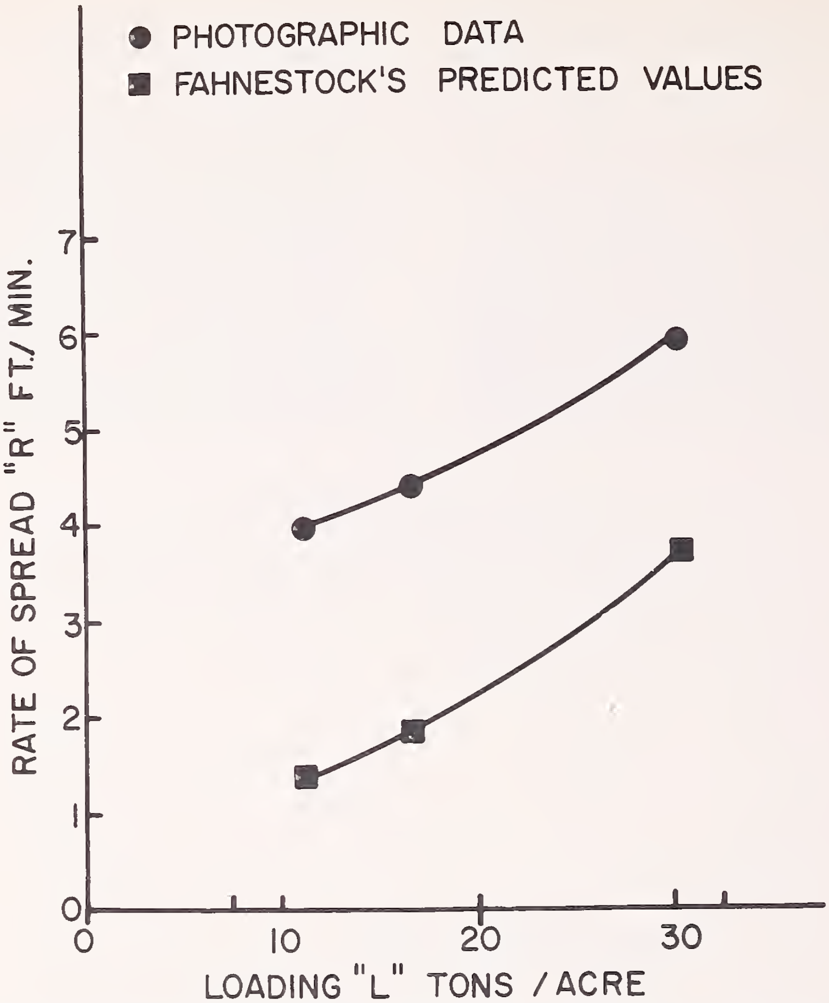

Figure 10. — Influence of loading on rate of spread in Douglas-fir comparing photographic average value with predictions from Fahnestock's equations.

distances between stations, uniform spreads were measured which produced usable results. Figures 9 and 10 show the comparison of the average rates of spread measured by photography with the rate of spread predicted by Fahnestock's equations.

Our experiments indicated that loading influences rate of spread, but that the wind is a stronger influence. The effect of wind upon rate of spread was studied for each species without segregating the data for loading or fuel moisture. An exponential function appears to fit the data the best, and regression analysis of the logarithm of rate of spread against wind velocity gave a separate equation for each fuel type.

$$R_{LP} = 3.48\ e^{.00192U}$$

where

R_{LP} = rate of spread of lodgepole pine fuel beds—ft./min.

U = windspeed—ft./min.

The equation was derived for windspeeds from

−400 to +400 ft./min.

$$R_{DF} = 2.66\ e^{.00388U}$$

where

R_{DF} = rate of spread of Douglas-fir fuel beds—ft./min.

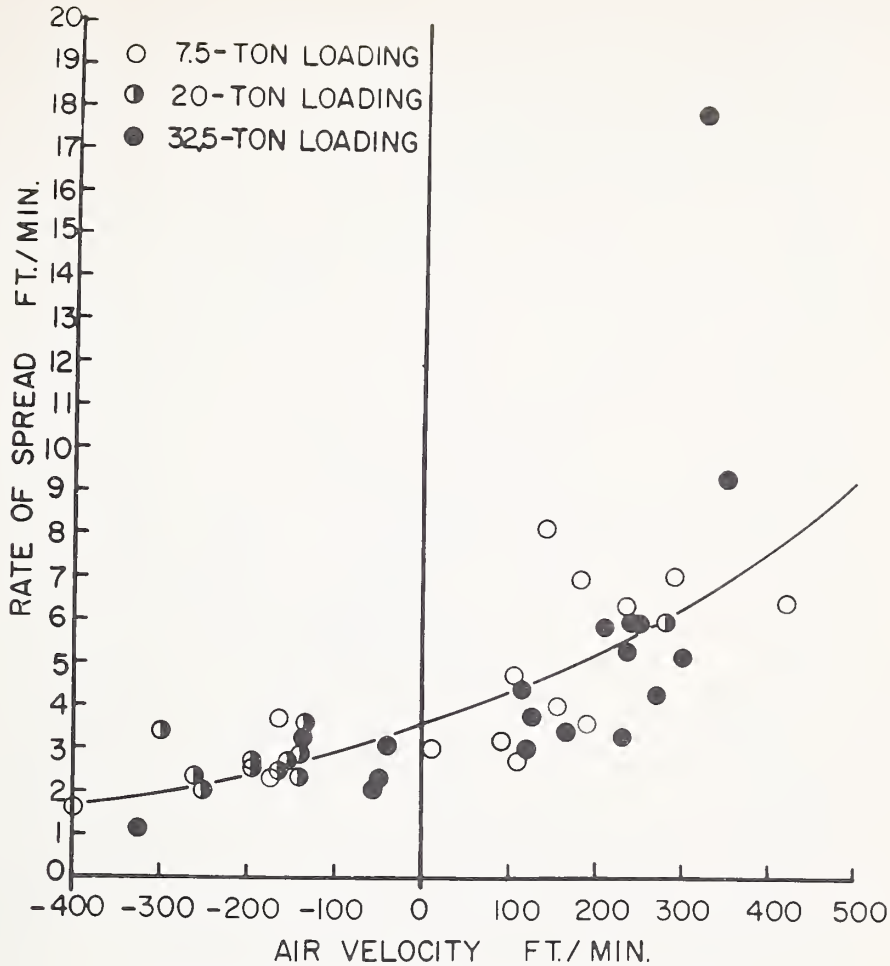

Figure 11. — Wind effects on rate of spread in lodgepole pine fuel beds.

Plots of these equations (figs. 11 and 12) show that the influence of wind largely overshadowed the effects of loading. For example, the three lodgepole pine fuel beds loaded at 32.5 tons per acre had average rates of spread vs. average windspeeds:

R	U
9.1 ft./min.	327 ft./min.
5.3 ft./min.	267 ft./min.
3.5 ft./min.	58 ft./min.

Rate of spread is proportional to loading and windspeed. However, not enough test samples were obtained to describe the relationship accurately. More laboratory work will help establish this, and later fieldwork will indicate the relation between laboratory and field fires.

Flame depth. — Measurements of flame depth by photographic and electronic methods (fig. 13) agreed so poorly that we know one or both techniques need improvement. The most probable causes of error were: placement of thermocouples too high above the fuel bed; misjudgment of flame depth because the flame front was skewed; and parallax effects because of camera angle. Since more photographic measurements were available,

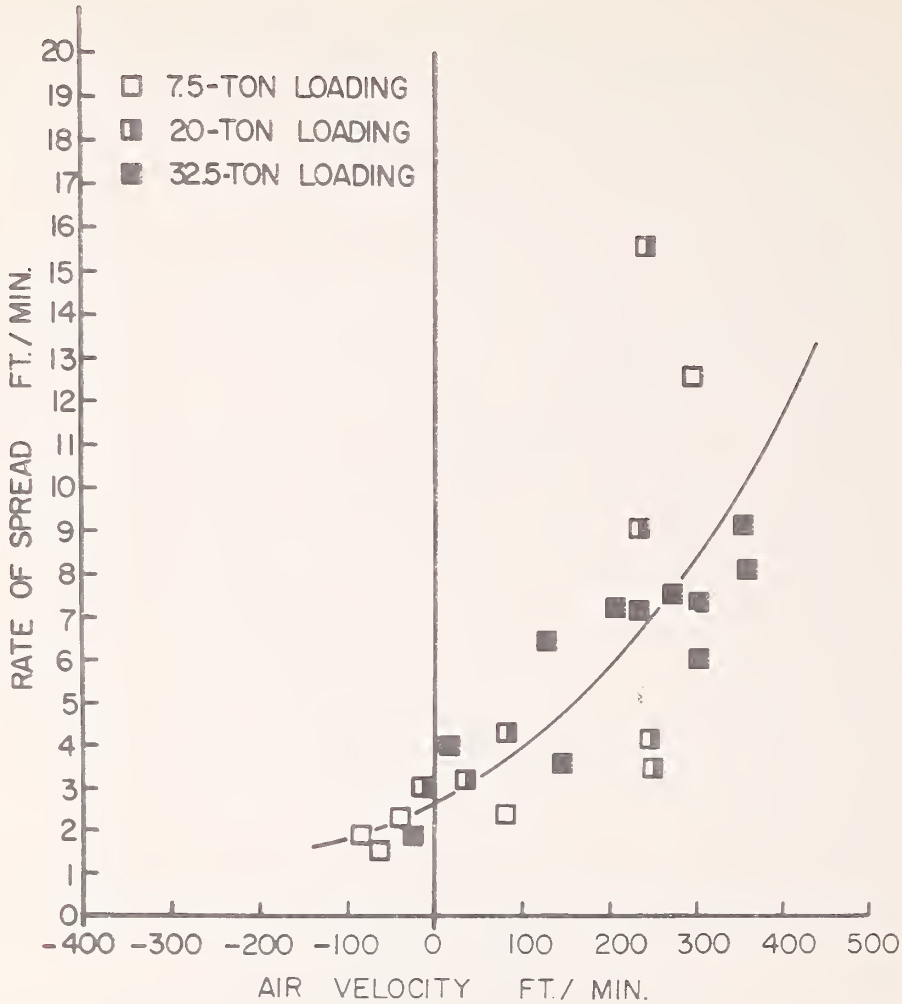

Figure 12. — Wind effects on rate of speed in Douglas-fir fuel beds.

they were used in later calculations of combustion rate.

Combustion rate. — Combustion rates calculated from the equation:

$$G = \frac{R \times W}{D}$$

where

G = unit area burning rate, lb./min./ft.^{2}

R = rate of spread, ft./min.

W = loading, lbs./ft.^{2}

D = flame depth, ft.

are plotted against loading (fig. 14). The effect of loading appears to be the same for both fuels, but characteristics of the fuels cause the burning rates to be different. The primary fuel particle size may be important. The same principles developed by Thomas (1963) and Fons (1962) on diffusion flames should apply to the test fires in the field. The major difference is that the field fires could not be considered symmetrical and probably were offset for this reason. The relation used for determining the diffusion flame characteristics of these fires was:

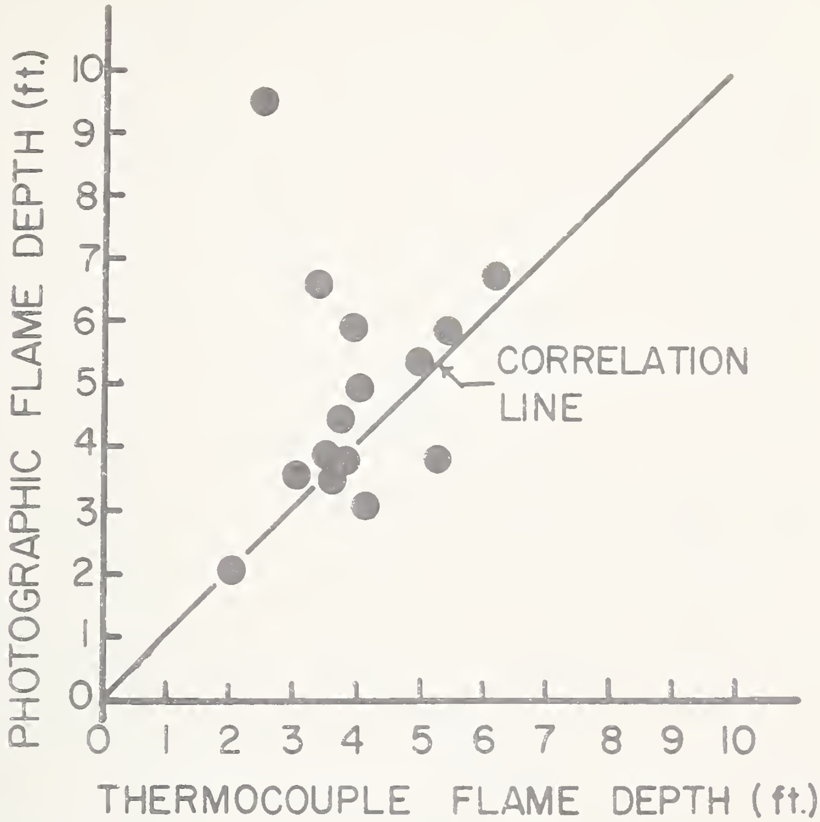

Figure 13. — Correlation between photographic and thermocouple measurement of flame depth.

$$\frac{L}{D} = K\left(\frac{G}{\rho(gD)^{1/2}}\right)^n$$

where

L = flame length, ft.

D = flame depth, ft.

G = unit burning rate, lbs./min./ft.^{2}

ρ = air density, 8.1×10^{-2} lb./ft.^{3}

g = acceleration constant, 1.152×10^5, ft./min.^{2}

and K and n are constants of the function. This analysis shows a family of curves that have nearly the same slope but different intercepts (fig. 15). Variation in the constants is shown in table 9.

Table 9. — **Fire characteristics' constants**

Test	K	n
Douglas-fir	13.7	0.630
Lodgepole pine	21.5	0.627
White pine	26.0	0.630
Ponderosa pine	55.0	0.607
Thomas'	42	0.610

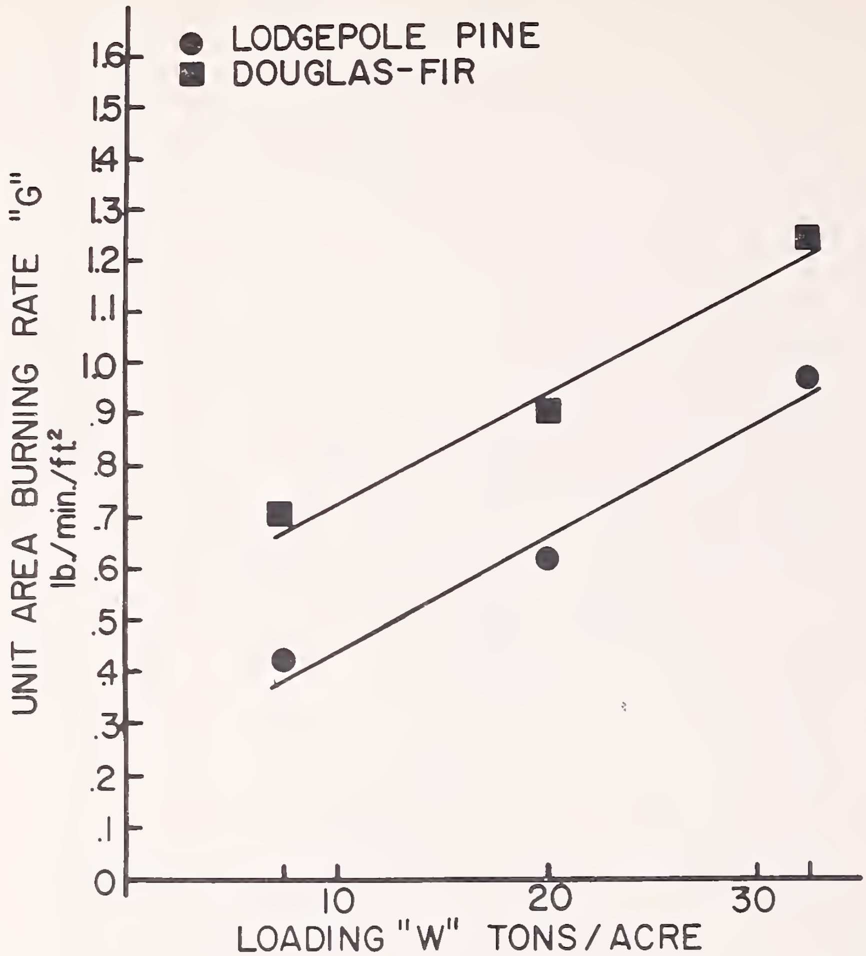

Figure 14. — The influence of loading on unit area burning rate is shown to be nearly linear. Average values for each loading were used.

The presence of a nearly constant exponent indicates the functional relation is essentially the same for laboratory and field tests. The variation in the intercept constant is probably due to inaccurate measurement of flame depth, overestimating G, the effects of wind, and underestimation of flame length. Additional laboratory tests, investigating the effects of wind and a system to measure weight loss, are being analyzed and will be reported later.

Vertical temperature profile. — Each fuel type shows a definite separation according to loading. Apparently the Douglas-fir fires were not as hot as the lodgepole pine fires, and loading seemingly had greater influence upon Douglas-fir. The lodgepole pine fires at 20 tons per acre and above did not increase in intensity very rapidly (figs. 16 and 17). These temperature indications do not agree with the fire intensity or burning rate calculations. This discrepancy points out that temperature measurements alone cannot give reliable conclusions. More must be known of the fire phenomena to allow intelligent use of these measurements.

Convection column velocity. — Analysis showed that only the data taken above the maximum flame height were meaningful. Many data points were taken within the

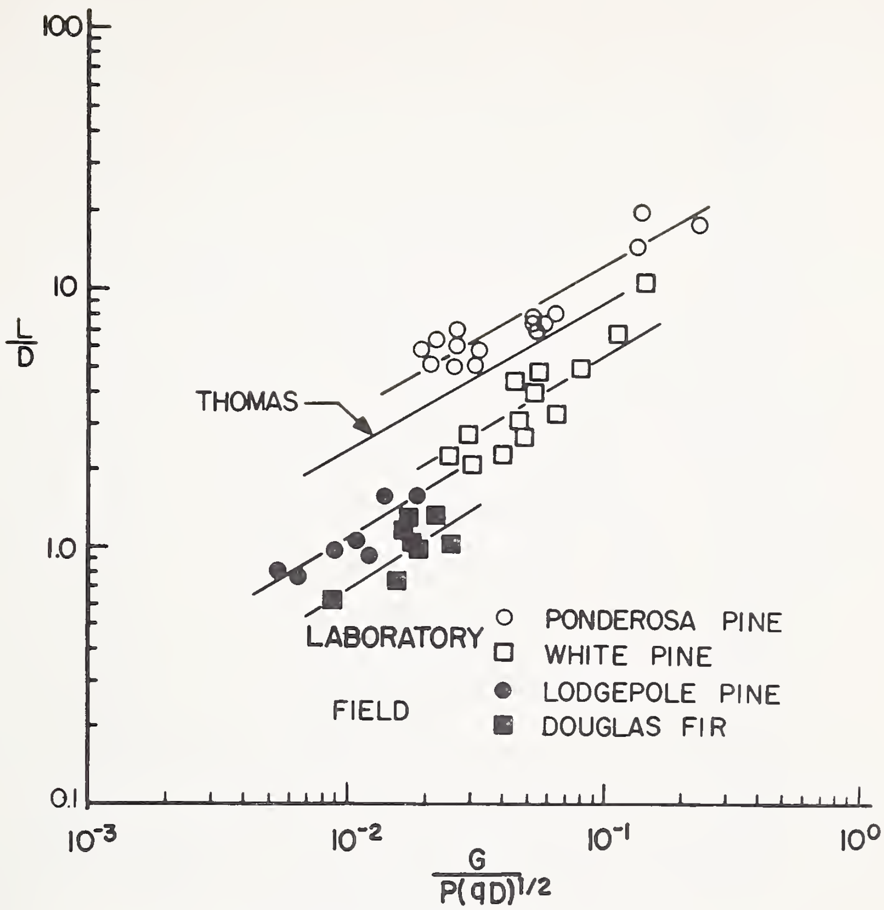

Figure 15. — Diffusion flame characteristics of laboratory and field test fires.

flame and had to be rejected. As a consequence, no relation between flame height and convection column velocity could be found. The sporadic nature of the data, because of wind influences, did not permit a complete description of the convection column velocity profile. The convection column energy therefore could not be computed, and no meaningful relation between fuel bed loading and convection column energy or velocity could be found.

However, there were sufficient data to show a relation between convection column velocity and temperature. The buoyancy force is directly proportional to the differential temperature between the gas and its surroundings. Because the relation between force and pressure is direct, a straight-line relation should exist between the dynamic pressure and the differential temperature. A plot of $q(\frac{T}{T_o})$ vs. $T-T_o$ (fig. 18) shows the data taken above maximum flame height. The straight-line equation for these data is:

$$q\left(\frac{T}{T_o}\right) = 4.07 \times 10^{-4}(T-T_o)$$

where

q = dynamic pressure—lb./ft.^{2}

T = convection column temperature—°F.

T_o = ambient temperature—°F.

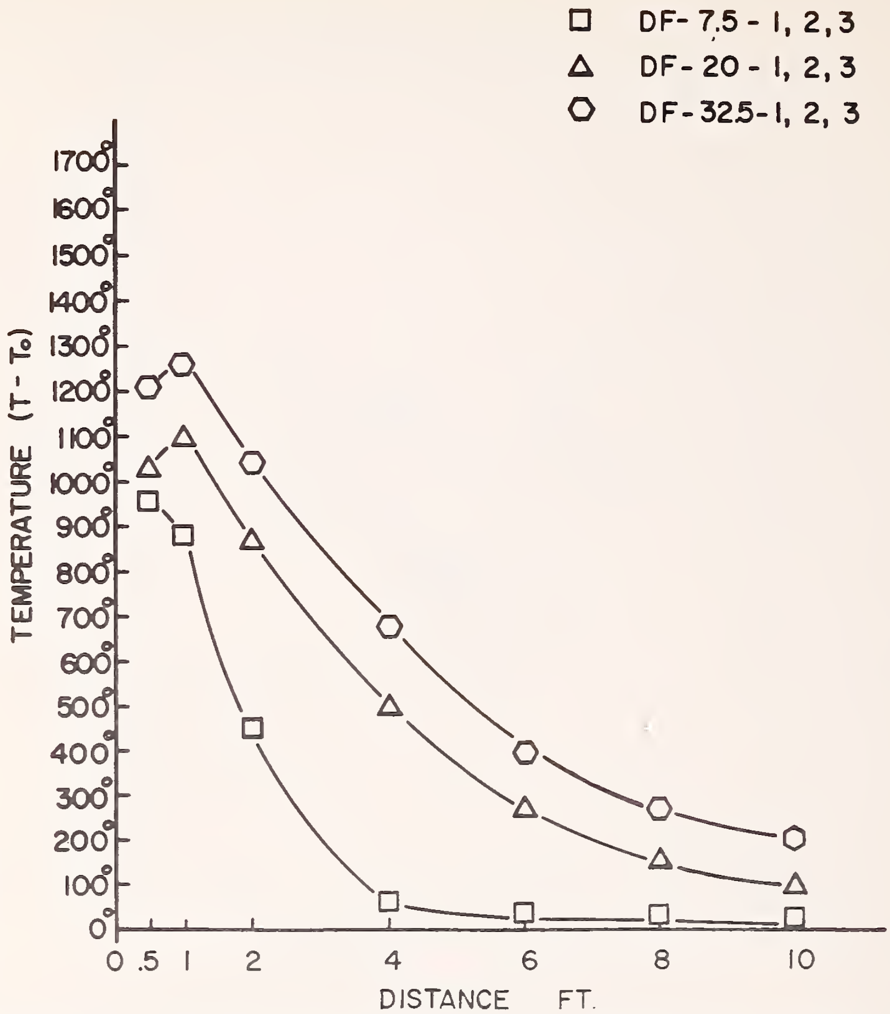

Figure 16. — Vertical temperature profile for Douglas-fir as measured in the flame zone.

The regression coefficient for this equation is 0.715 with 32 data points.

The velocity of the convection column is computed from the formula:

$$q = \frac{\rho V^2}{2g}$$

which reduces to:

$$V = \sqrt{\frac{(2g)}{\rho_0} \quad \frac{(qT)}{T_o}}$$

where

V = convection column velocity—ft./sec.

g = acceleration of gravity = 32.2 ft./sec.^{2}

p_o = ambient air density—lb./ft.^{3}

substituting for $q(\frac{T}{T_o})$ and evaluating gives:

$$V = 0.626 \sqrt{T - T_o} \text{ ft./sec.}$$

This equation was plotted with the experimental data shown in figure 19. The convection column gas was assumed to be air in an atmospheric static pressure of 13.5 p.s.i.

Fuel bed compactness. — Comparison of

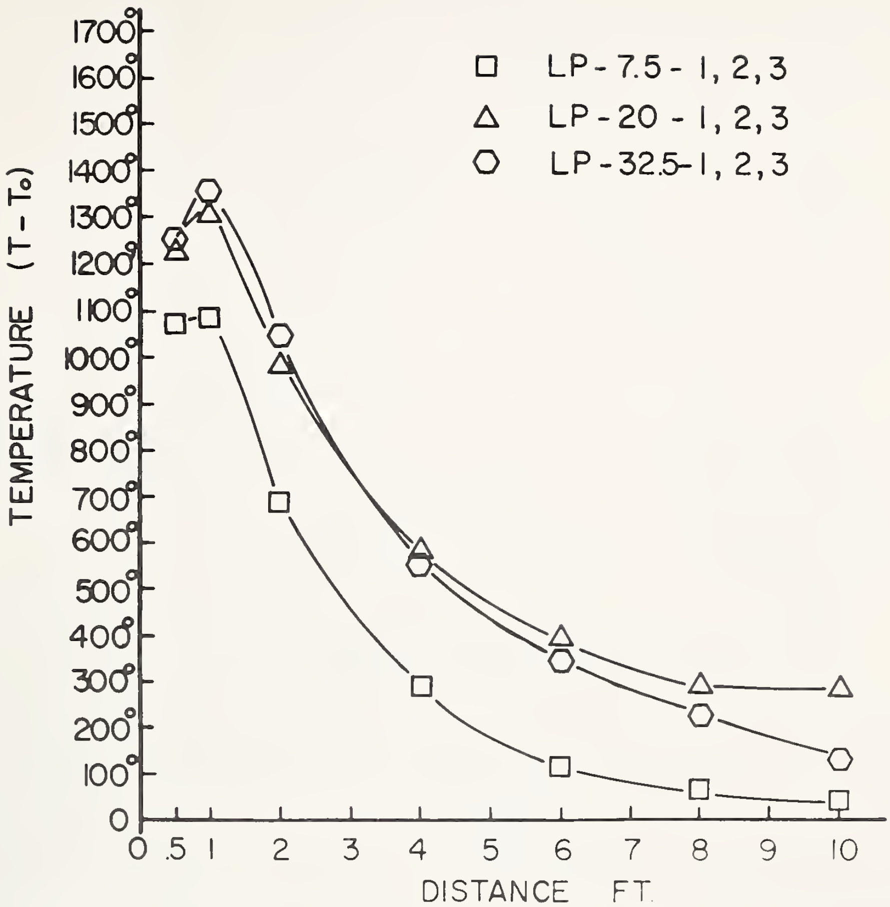

Figure 17. — Vertical temperature profile for lodgepole pine as measured in the flame zone.

compactness for needle fuel beds and dimensioned wood crib fuel beds showed definite differences in rate of spread at the same compactness values. By using the field data, laboratory data, and data of Fons et al. (1960), we analyzed the effects of compactness on rate of spread. The data used were for fires burned at moisture contents between 7 and 10 percent (table 10). Because of the limited number of points, this analysis shows only the separation of results in these two types of fuel bed models and the general trend: as compactness increased the rate of spread decreased (fig. 20). The relation has the form of:

Needle fuel beds $R = 95.3\ (1/\lambda)^{-1.05}$

Wood crib fuel beds $R = 12.5\ (1/\lambda)^{-1.30}$

where

R = rate of spread, ft./min.

and

$1/\lambda$ = compactness, ft.^{2}/ft.^{3}

Additional work incorporating the effects of fuel particle size may bring the two curves much closer.

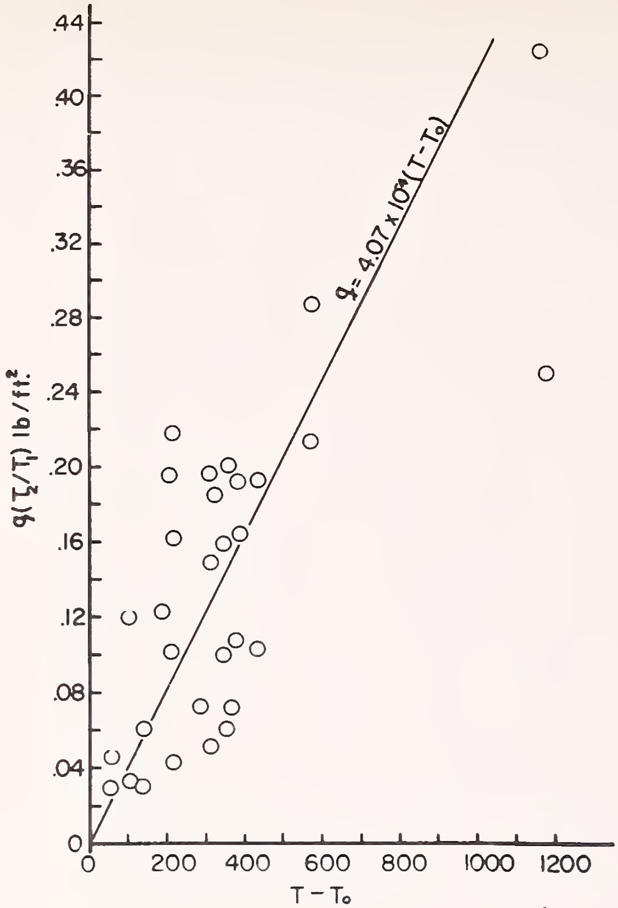

Figure 18. — Corrected dynamic pressure as a function of temperature for points above the flame.

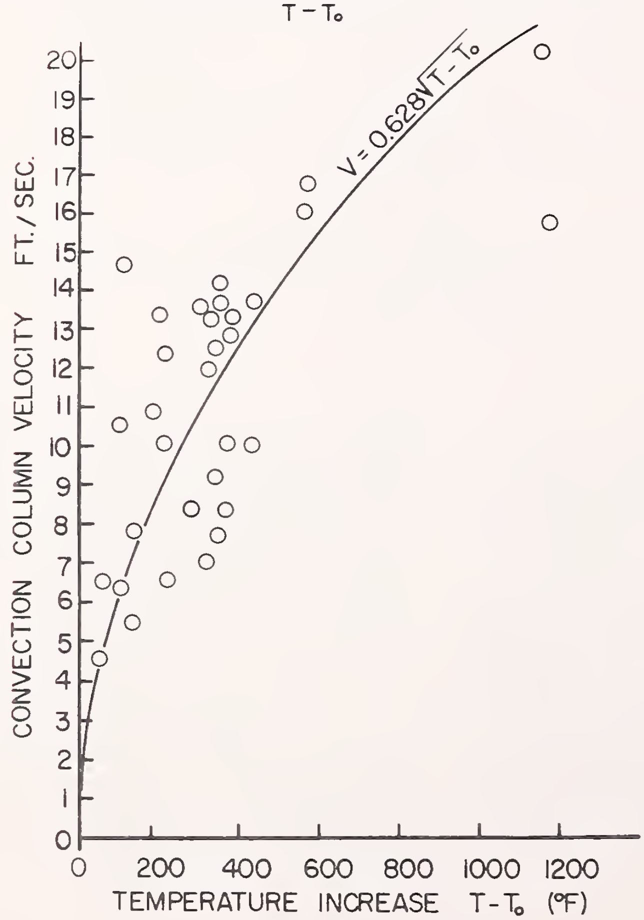

Figure 19. — Convection column velocity as a function of temperature at maximum flame height.

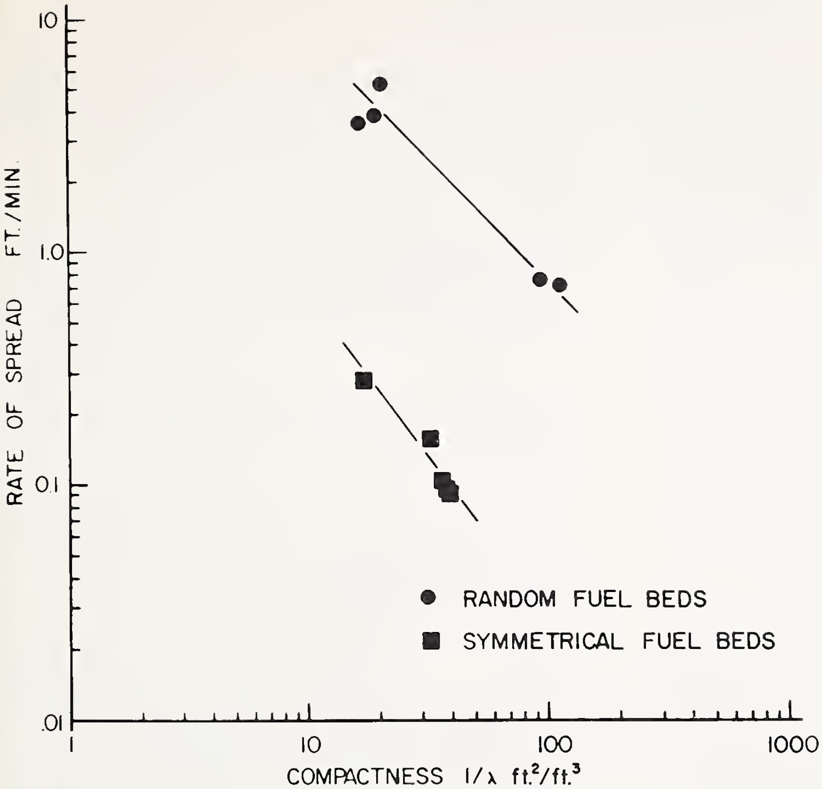

Figure 20. — Influence of compactness on rate of spread in two different fuel bed models.

Table 10. — **Compactness and rate of spread of random and symmetrical fuel beds**

Random fuel bed	Compactness	Rate of spread	Symmetrical fuel bed	Compactness	Rate of spread
	$Ft.^2/ft.^3$	F.p.m.		$Ft.^2/ft.^3$	F.p.m.
Lodgepole pine (32.5 T/A)	18.2	3.5	Wood crib No. 1[1] 2″ × 2″ sticks	17.7	0.275
Douglas-fir (20.0 T/A)	20.4	3.7	Wood crib 0.5″ sticks	33.8	0.156
Douglas-fir (32.5 T/A)	23.8	5.1	Wood crib 0.75″ sticks	37.3	0.103
Ponderosa pine (laboratory)	99.4	0.74	Wood crib 1.00″ sticks	39.8	0.096
White pine (laboratory)	119.0	0.68	Wood crib 1.25″ sticks	40.5	0.092

[1]Crib No. 1 was burned at the Forest Fire Laboratory, Missoula, Montana. The remainder of the wood cribs were prepared by Project Fire Model. The apparent disparity in compactness between crib No. 1 and the fire model cribs is caused by spacing differences.

CONCLUSIONS

1. Reproducible fuel beds were best prepared when the slash was procured from recently cut trees. Such trees were so uniform in moisture content that theoretical dry weight loadings of plots were easily achieved. Measurements of moisture in older slash deviated so widely that it was difficult to attain predetermined dry weight loadings.

2. This study strikingly demonstrated that a large percentage of logging slash is limbs and twigs of small diameter. The fuels that propagated the main forward spread of fire — needles and branches one-fourth inch and less in diameter — accounted for more than one-third of the dry weight of slash in the lodgepole pine and Douglas-fir plots.

3. Fire intensities can be correlated by relating flame length to the B.t.u./min./unit length of fireline front. However, more detailed information is required about fuel and fuel bed characteristics before various fire models can be compared directly. Prepared slash type fuel beds burned with intensities comparable to those reported by Byram for wildfires. This type of fire model may allow studies of characteristics associated with wildfires.

4. Fuel bed loading influenced rate of spread in a manner similar to that reported by Fahnestock. Higher rates of spread were experienced in our study because of the firing technique used. A wider range of loadings should be tested to determine the functional relation between loading and rate of spread.

5. Field and laboratory fires can be characterized by buoyant diffusion flame analysis using a general equation of the form

$$\frac{L}{D} = K\left(\frac{G}{\rho(gD)^{1/2}}\right)^n.$$

The distribution of data indicates the need for additional tests to refine the measurements of flame length, flame depth, and unit area burning rate.

6. Air velocity was more influential than loading on rate of spread. The relation between air velocity and rate of spread was an exponential function for both fuels tested. Additional laboratory and field testing will be necessary to separate the effects of air velocity and loading.

7. Measurements of convection column velocity are difficult to obtain in the field because of the effect of ambient winds. In spite of this difficulty, a relation between column velocity and temperature was established. Hence velocity of the convection column may be estimated if the temperature can be measured. Temperature profiles can be obtained but must be integrated with other fire parameters to be useful in fire analysis.

8. Comparison of rates of spread between needle and wood crib fuel beds showed large differences. These differences are attributed to the fuel particle size and its arrangement in the fuel bed. A careful analysis of fuel particle surface area-to-volume ratio and fuel bed compactness should account for most of the differences in the fire models.

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